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OF WALL SHEAR STRESS IN 'BLASTANE' EXPERIMENTS

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ABSTRACT

Buried Wire Gages operated from a Constant Temperature Anemometer System are among the special types of instrumentation to be used in the Boundary Layer Apparatus for Subsonic and Transonic flow Affected by Noise Environment ('BLASTANE'). These Gages are of a new type and need to be adapted for specific applications. Methods were developed to fabricate Gage inserts and mount those in the 'BLASTANE' Instrumentation Plugs. A large number of Gages were prepared and operated from a Constant Temperature Anemometer System to derive some of the calibration constants for application to fluid-flow wall shear-stress measurements. The final stage of the calibration was defined, but could not be accomplished because of non-availability of a suitable flow simulating apparatus. This report provides a description of the Buried Wire Gage technique, an explanation of the method evolved for making proper Gages, the procedure for calibrating the Gages and the results of measurements performed for determining two of the calibration constants, namely Temperature Coefficient of Resistance and Conduction Loss Factor.

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NOMENCLATURE

- A - Conduction Loss Factor.
- B - Equivalent Length Factor
- b - span of the sensing element.
[clear length between the electrical leads].
- (C/H) - Overheat Reference Value Calibration Slope.
[Proportionality constant for the relationship between the Overheat Reference value and the Resistance Factor for the Anemometer System].
- d - Length of the sensing element in flow direction.
[diameter for wire element placed cross to flow].
- h - Measured total heat transfer rate with the Gage sensing element exposed to flow.
- h
r - Calculated conduction heat transfer rate from the Gage sensing element to the substrate material.
[with the sensing element at operating temperature as set by the operating resistance, and the substrate at the local flow recovery temperature]
- h
o - Measured total heat transfer rate with Gage sensor placed in a no-flow condition [during calibration].
- k - Thermal conductivity of the flow medium at 'wall' conditions [i.e. at sensor operating temperature]
- k
sub - Thermal conductivity of the substrate evaluated at appropriate substrate temperature.
['recovery' temperature when placed in flow, or the substrate/ambient temperature for calibration in the absence of flow].
- Nu - Nusselt Number for the flow-related heat transfer with Gage sensor at the operating resistance.
- (O/H) - Overheat Reference value obtained from the Overheat Reference function of the Anemometer System.
- p - Static Pressure at the Gage location in Flow.
- p' - Static Pressure Gradient in streamwise direction at the Gage location in flow. [$-(dp/dx)$].
- Pr - Molecular Prandtl Number of the flow medium at 'wall' conditions.
- R
ca - Resistance of the cable connecting the Gage sensing element to the Anemometer System.

LIST OF SYMBOLS (Continued)

- R = Resistance of the Gage sensing element.
- R_r = Resistance [at local 'recovery' conditions] of the Gage sensing element with the Anemometer System in 'STANDBY' mode, and with flow passing over the Gage.
- R_s = Operating resistance of the Gage sensing element. [set on the Anemometer System].
- R_{std} = 'Standard' Resistance value for the Gage sensor, at the reference temperature [usually 20 deg.C].
- R_0 = 'Cold' [at ambient conditions] resistance of the Gage sensing element for calibration measurements.
- R_1, R_2, R_3, R_4 = Anemometer Bridge Resistance Values. [for the four arms of the bridge].
- (R/F) = Resistance Factor related to the operate resistance setting and the actual sensor resistance, for the Overheat Reference function of the Anemometer.
- T = Temperature
- T_0 = Temperature of the substrate for calibration measurements. [ambient temperature].
- T_r = Local 'recovery' temperature of the wall flow. [equal to the temperature attained by the sensing element when it remains unheated by the anemometer system. This is deduced from the measured Gage sensing element resistance value in flow].
- T_s = Operating temperature of the Gage sensing element. [deduced from the operating resistance setting].
- T_{std} = Reference temperature (20 deg.Law) for specifying the Gage Resistance-Temperature law.
- V = Voltage supplied to the bridge circuit by the anemometer system with flow passing over the Gage.
- V_0 = Voltage supplied to the bridge circuit by the anemometer system without any flow on the Gage.
- x = Distance vector in streamwise direction.
- α = Temperature Coefficient of Resistance.
- μ = Coefficient of absolute viscosity for flow medium.
- ρ = Density of flow medium at wall conditions
- τ_w = Wall Shear Stress in fluid flow.

1. INTRODUCTION

Detailed measurements of fluid flows have been the major basis for successful development of advanced design and analysis methods pertaining to flight vehicle flow fields and other practical fluid flow situations. Different aspects of flow phenomena call for different sets of detailed measurements, perhaps using different flow measurement techniques. Among the many facets of fluid flow, boundary layer transition, especially in high speed flows, has been a subject of intensive study for a long time now; but, more detailed measurements are needed to obtain an adequate understanding that can lead to reliable prediction methods [Ref. 1]. Special apparatus such as the Boundary Layer Apparatus for Subsonic and Transonic flows Affected by Noise Environment ['BLASTANE'] have been developed to generate a variable flow environment suited to detailed studies on the effects of the many factors that influence the transition phenomena [Ref. 2]. However, existing conventional flow instrumentation cannot provide the desired spectrum of detailed measurements of transition region. A new technique is needed to non-intrusively measure wall flow properties, such as wall shear stress. One very promising technique is the Buried Wire Gage technique which uses the heated element concept for providing a measure of wall shear stress [Ref. 3].

The heated element concept was conceived several decades ago; but, application of that concept in practical flow situations remained a formidable problem for a long time because of the lack of a proper sensor that could provide an adequate level of sensitivity. Typically, the heated element concept consists of a sensing element that is arranged flush to the wall surface in a flow. The element is heated to an appropriate temperature so that the characteristics of heat transferred to the wall layer of flow may be measured. In reality, the measured heat transfer rate is the total heat transferred from the heated element and this has a certain proportion accountable to the heat lost by thermal conduction to the substrate material surrounding the heated element. This proportion could be rather large for most choices of conventional substrate materials such as pyrex, quartz, plexiglass, etc, which have been used for the 'hot film' type of sensing elements. Another aspect of the heated element concept that relies heavily on the characteristics of the sensor is the streamwise extent of the sensing element in the flow. Part of the measured total heat transfer consists of the effects of local pressure gradients in the flow. These effects must be properly accounted for before the component of measured heat transfer related solely to the wall flow may be extracted and converted to wall shear-stress. The pressure gradient component is directly proportional to the streamwise extent of the sensing element and therefore may be reduced only by making the sensing element appreciably slender.

Past experience with the heated element concept has shown that special Gages such as the Buried Wire Gages are required to perform reliable measurements of wall flow shear stress [Ref. 1]. The Buried Wire Gage consists of a very slender wire (a few microns in diameter) which is spot welded at its ends to a pair of electrical leads that are flush-embedded on a low thermal conductivity substrate. The wire is firmly attached to the substrate surface by a bonding process. The Buried Wire Gage may be installed in a fluid flow 'wall surface', and operated from a constant temperature Anemometer System to finally provide a measure of wall shear stress.

Buried Wire Gage technique has been identified as one of the major flow measurement techniques for experiments in the BLASTANE apparatus, specifically to measure the effects of acoustic noise, its frequency content, free stream turbulence, and Mach number on boundary layer transition phenomena. Detailed data on such effects do not exist now, primarily because of the difficulty in making detailed measurements close to the wall in the boundary layer region. The Buried Wire Gage technique is ideally suited to such detailed flow measurements because the sensing elements are non-intrusive to boundary layer flow and therefore permit simultaneous measurements all along the flow development length on the wall. In the present context, Buried Wire Gages built into the Instrument Plug Blanks of the BLASTANE apparatus would be used to collect the desired detailed data on the flow in the BLASTANE Test Section. From this data base, correlations are to be evolved to help establish reliable methods for predicting boundary layer transition behavior in actual flow situations.

Special care has been taken to incorporate proper Gages in the instrument plug blanks of the BLASTANE apparatus. The Gages needed to be precisely flush to within a few microns on the Instrument plug surface in order that the measurements be reliable. The Instrument plugs had been fabricated to a high degree of accuracy and surface finish so that the wall layer of flow, as it passes from the BLASTANE Test Section wall surface to the Instrument Plug surface, would experience very little disturbance. The Gages must maintain this level of non-interference to the flow so that the measurements can reflect the small changes that occur in boundary layer flow for low levels of free-stream disturbances.

Each of the total of 23 Plugs of BLASTANE have been provided with a row of five buried-wire Gages, oriented cross-wise to the airflow. Past experience in building this type of Gages has shown that even the best control on fabrication accuracies did not render the different Gages identical in terms of calibration constants. A similar result was expected for the present set of Gages; and hence, calibration procedures were intended to be repeated for each Gage.

The present report describes the different aspects associated with development of the Buried Wire Gages. The specific aspects are: principle of the Buried Wire Gage technique, the instrumentation used in performing the calibration experiments, the three step calibration procedure for determining the complete calibration data of the Gages, and the results of calibration measurements.

2. BURIED WIRE GAGE TECHNIQUE

The Buried Wire Gage technique of measuring wall shear stress in fluid flow is based on the similarities that exist between the mechanisms of momentum transfer and heat transfer [see Fig. 1]. In a fluid flow past a solid wall surface, the flow layer next to the wall surface is heavily influenced by the effects of viscosity. This flow layer, called the boundary layer, may itself be regarded as being composed of several inner layers, each distinguished by the relative dominance between the effects of molecular viscosity on the one hand and the influence of random fluid particle motions on the other. The inner layer immediately adjacent to the wall surface is called the laminar sub-layer and is characterized by the exclusive dominance of molecular viscosity effects. Within this sub-layer, the flow is such that a unique relationship exists between the momentum transfer process and the heat transfer characteristics for any given fluid, irrespective of the nature of the outer flow. This is the basis for measurement of wall shear stress with the Buried Wire Gage technique.

Application of this technique to a practical flow situation requires a sensing element mounted flush to the flow surface. The element is heated to a desired excess temperature higher than that of the local fluid flow adjacent to the wall. The rate of heat transferred from the sensing element needs to be measured for any given sensor temperature. A Buried Wire Gage is an ideal sensor in this respect because it may be operated from any existing constant temperature anemometer system which provides a convenient method of monitoring the heat transfer rates.

An added merit factor for the Buried Wire Gage arises from the smallness of the sensing element associated with it. It has a small slender sensing element which, when heated, produces effects that are entirely confined to the laminar sub-layer, and thus becomes amenable to a unique set of governing equations which remain invariant with respect to the status of outer boundary layer flow. In particular, the calibration equations need no modifications for a wide variety of flow changes such as those that occur as the boundary layer flow undergoes the transition phenomenon. This added advantage is highly relevant in the context of flow measurement with heated element techniques, which have often been abandoned by

experimenters simply because of the need to undertake extensive calibrations before measuring the different aspects of fluid flow phenomena in any given overall flow situation.

A convenient method of heating the Buried Wire Gage sensing element and monitoring the heat transfer rate is to use a constant temperature anemometer system. Typically, such an anemometer system permits setting of a desired sensor operating temperature in terms of the corresponding resistance value, which then becomes the control reference to the system. A feedback circuit in the anemometer system provides a continuously regulated heating current to the Gage sensing element, just enough to heat and maintain the sensing element at the desired operating temperature. The electrical power required to produce that heating current is then a measure of the heat transfer rate from the sensing element to all of its surroundings, which includes the flow medium and the substrate material. The characteristics of the feedback circuit are such that the anemometer system is able to respond to fast changes in the flow.

The relationship between heat transfer rate and wall shear stress for a Gage sensing element flush to the wall surface and oriented perpendicular to the flow direction, is expressed in the form of a calibration law [Ref. 3].

$$\tau_w = 1.9 \frac{\mu^2}{\rho (Pr)} \frac{Nu^3}{(B d)^2} - 0.2778 \frac{(B d)(p')}{Nu} \quad \dots (1)$$

where,

$$Nu = \frac{h}{k_b (T_s - T_r)} - (A) \frac{k_{sub}}{k} \quad \dots (2)$$

It may be noted, that Eq.(1) gives the relationship between the wall shear stress and a dimensionless variable called 'Nusselt Number', which is constructed from only the flow-related heat loss, as explained in Eq.(2). The parameter 'h' in Eq.(2), is the measured total heat transfer rate from the sensing element, whereas the entire term containing the Conduction Loss Factor A represents the portion of heat lost by thermal conduction to the substrate. The Nusselt Number Nu, then represents just the flow-related heat transfer rate.

The factors A and B are to be determined from calibrations in known flow situations. It has been demonstrated that these factors may be determined from two simple measurements: one with the Gage operating in a no-flow constant temperature environment, and the other with the Gage operating in a flow of otherwise known wall shear stress [Ref. 3].

3. INSTRUMENTATION

The instrumentation used in the present series of experiments consisted of the different Buried Wire Gages, which were to be calibrated, and the associated operating as well as measurement instrumentation, namely a 16-Channel Constant Temperature Anemometer System, an Environmental Testing Chamber, and the BLASTANE Calibration Tube.

Of these, the BLASTANE Calibration Tube which has been designed to provide a flow of 'known' wall shear stress was not operational at the time of writing this report and therefore is not fully described in this report. It may be of interest to note in passing that the BLASTANE Calib Tube consists of a long uniform-bore tube assembly, one section of which can accommodate the Instrument Plugs in such a manner as to expose the Gages to the flow inside the tube. The uniform-bore section ahead of the Plug installation station is long enough to provide a 'fully developed pipe flow' pattern at the Plug station. This flow pattern implies that the flow speed profile that remains invariant down the tube length and, as a result, the wall shear stress may be determined from a simple measurement of the static pressure gradient in the flow. Wall static pressure taps may be used to measure the static pressure variation along the length of the tube in the vicinity of the Plug station, and these measurements may be applied to the well known pipe flow governing equations to derive the local wall flow shear stress. Thus, for any flow condition in the Calib Tube, the wall shear stress becomes a 'known' quantity, and serves to calibrate the Gages.

The calibration measurements presented in this report are entirely confined to the determination of the Conduction Loss Factor 'A' [see Eq. 2] for the different Gages. The instrumentation pertaining to this phase of the calibration is described in the following paragraphs:

3.1 BURIED WIRE GAGES

Buried Wire Gages are relatively of recent origin. Typically, a Buried Wire Gage consists of a substrate insert in which is embedded a pair of electrical leads. Attached to the top of these leads and bonded flush to the substrate surface is a very thin wire of about a few microns in diameter. The top of the leads and the wire are flush to the substrate surface

which itself is to be placed flush to the flow surface of interest. The basic idea is that the Gage should not in any manner disturb the flow adjacent to it when installed in a flow environment. Development of these Gages for use in BLASTANE experiments progressed along three major phases: choice of materials and methods, preparation of the substrate insert, and mounting of the sensing element, as described below.

3.1.1 CHOICE OF MATERIALS AND METHODS

The primary factors that affect the quality of the Buried Wire Gage were known to be Substrate Material, Sensing Element, and amenability of this combination of materials to a suitable Bonding technique that would attach the sensing element to the substrate surface.

It was recognized that the substrate material acts as the support to the sensing element in producing a robust Gage, but also would become the major source of measurement uncertainties because of its relatively high contribution to the total heat transfer when the Gage is used for wall shear stress measurements. Improvements in measurement accuracies had been realized in the past by using a substrate material of very low thermal conductivity [Ref. 3]. The choice of substrate material was thus primarily dictated by the need to have the lowest thermal conductivity, although some extent of compromise was found to be necessary in order to seek adaptability to the fabrication process which involved embedding of electrical leads and bonding of the sensing element at the surface.

Among the limited choices of materials with low thermal conductivity, polystyrene and other styrene plastics, such as Rexolite and Lexan appeared to be appropriate for the present application. Of these, only the polystyrene (Styrolux) came in the form of crystals ready for use in injection molding. This property of injection moldability was important because of the need to arrange electrical leads. By placing the electrical leads in a mold and injecting molten polystyrene around it, substrate inserts of any size and shape could be easily formed. This proved to be much more economical than machining substrate inserts from pre-formed rod stock and embedding the electrical leads into those. Polystyrene was the final choice for substrate inserts.

Sensing element for Buried Wire Gages had to be very slender to assure that the heat transfer from it in flow would be entirely confined to a very thin flow layer. The choice was limited to tungsten, platinum, or platinum-iridium alloy, all of which were readily available in the form of slender wires. All these materials had been popular for use in hot wire anemometry because of several factors such as relatively low cost, better ductile properties, ease of manufacture and ready availability in small diameters. Of these, tungsten possessed

the highest tensile strength that makes for robust Gages, and thus became the preferred choice for present experiments. The tungsten wire used in the present Gages were of 4 micron diameter.

Bonding technique for attaching the sensing element to the substrate surface was to be carefully chosen to ensure that the element remained well attached to the surface, and yet did not acquire too thick a top-coating which otherwise would adversely affect the sensitivity of the final Gage. A review of existing literature on the subject of similar bonding applications revealed that one of the most successful methods would be the so-called 'Solvent Bonding Technique' which consisted of applying a small drop of an appropriate volatile solvent around the sensing element, so that the solvent may dissolve some of the surrounding substrate material to form a little bubble around the wire and then readily evaporate to leave behind a thin coating of the substrate material on the element [Ref. 3]. The solvent bonding technique was therefore chosen for the present Gages.

Thus, the choices of materials and methods for the present Buried Wire Gages were finalized as polystyrene for the substrate, slender tungsten wire as the sensing element, and 'Solvent Bonding Technique' for attachment of the sensing element to the substrate surface.

3.1.2 PREPARATION AND MOUNTING OF SUBSTRATE INSERT

The Gages were required to be arranged on specially shaped instrument plug blanks of the 'BLASTANE' (Boundary Layer Apparatus for Subsonic and Transonic Flow Affected by Noise Environment). Each plug was to have five Gages, with the sensing wires oriented spanwise to the axis of the curved faces of the plug [Fig. 2]. Each Gage would have a substrate insert mounted in a hole in the plug blank.

The substrate insert was required to be in the form of a flange topped cylindrical plug to suit the holes in the aluminum instrument plug blanks of BLASTANE [Fig. 2]. A clearance of about 0.125 mm (0.005 inch) was allowed between substrate insert and the hole in the instrument plug to allow for an epoxy to fill in and securely retain the substrate insert. The flange-top of the insert allowed for proper positioning of the insert so that the top face of it would become flush with the flow bearing surface of the plug. The flange-top configuration was evolved as a modification to the plain cylindrical configuration, which exhibited a tendency to undergo some dimensional distortions. The epoxy around the plain cylindrical inserts would shrink during a subsequent annealing process and pull the insert down into the holes in the plug blank. This recess at the sensing surface was unacceptable. The design of the inserts was therefore modified to include a flange top that would prevent any movement at the top face of the insert.

Fabrication of the Gage substrate inserts began with injection molding of polystyrene to obtain the substrate inserts. The polystyrene crystals were baked overnight in an oven set at 82 deg.C to expel any moisture content that might exist. These crystals were then fed into an injection molding machine and heated to 245 deg.C. This temperature setting ensured that the plastic would not burn and would still flow easily into a mold. The mold was designed to accommodate cylindrical adapters which had openings to align a pair of nickel electrical leads and hold those in place while the molten polystyrene was injected into the mold cavity. The entire mold was heated to the annealing temperature of polystyrene, namely 82 deg.C, and maintained at that temperature while molten polystyrene from the injection molding machine is injected into the mold cavity. Care was taken to keep the mold between 82 deg.C and 93 deg.C, during the entire duration of injection casting. Lower temperatures would cause residual thermal stresses in the polystyrene material, whereas higher temperatures would cause burning and degradation of the polystyrene material. The molded polystyrene insert was then removed from the mold cavity and the cylindrical adapters were gently pulled away from the insert. The runners and other protrusions of excess polystyrene inherent to the design of the mold were snipped off each insert and the entire batch was allowed to anneal for several hours in an oven set for 82 deg.C. The different stages of fabrication of the insert blank are depicted in Fig. 3.

The inserts were carefully deburred and the extra length of the electrical leads at the sensor face of the insert were snipped off. This surface was polished by hand-stoning on a fine polishing stone with the insert secured in an insert holding block [Fig. 3]. The inserts were annealed again after stoning to relieve any residual stresses that might have accumulated in the substrate material.

The nickel electrical leads of the insert were attached to coaxial cables to facilitate easy electrical connections. The next step was to mount the inserts in the holes provided in the aluminum instrument plug blanks of BLASTANE apparatus. A small quantity of a relatively slow setting epoxy such as BIPAX TRA-BOND BB 2101 was used at the flange-top corner to allow enough time for proper alignment of the insert. The insert when properly aligned would have its electrical leads appearing spanwise to the axis of curvature of the plug blank flow surface. Once the insert was properly aligned, the attachment of the insert to the plug was rendered firm by filling an epoxy at the back end of the insert hole. The plug with all the inserts was then baked in an oven, starting at 38 deg.C and increasing the temperature by 5.6 deg.C every ten minutes until 82 deg.C was reached, at which it was baked for an hour and then allowed to cool with the oven switched off. This process of baking seemed to be an effective method of assuring that the insert would be properly held by the epoxy and thoroughly stress relieved.

The faces of the inserts were next carefully polished down with a fine jeweler's file till the surfaces were flush to within 5 microns on the curved face of the instrument plug. If this step involved much polishing, the entire plug was placed in an oven set at 82 deg.C to relieve any residual stresses in the insert material. Next, the surfaces of the inserts were hand-stoned with a cylindrical stone to achieve a high level of flushness and polish that could match with the curved plug surface. The fabrication method is described in greater detail in Ref. 4. The inserts were, at this stage, ready for mounting of the sensing element.

3.1.3 MOUNTING OF SENSING ELEMENT

The sensing element, in the form of a slender tungsten wire of 4 micron diameter, was properly aligned between the top of the electrical leads and tacked down to the substrate surface with a piece of adhesive tape so that it would be under a slight tension. The wire was then spot-welded to the electrical leads and the excess length of the wire was snipped off. Care was taken to ensure that the welding process did not excessively heat the substrate around the electrical leads.

The final step in mounting the element was solvent bonding. It was recognized that a strong solvent may cause unwanted changes in the substrate material and render it difficult to produce the desired level of surface finish. However, the solvent had to be sufficiently strong and volatile to cause a proper deposit of the substrate material on the top of the wire. After several trials with a few solvents, ethyl acetate was finally chosen. A syringe-type applicator was used to deposit a single drop of the solvent that would submerge the entire length of the wire. Any excess solvent was withdrawn into the syringe. The solvent would dissolve a thin layer of the substrate around the wire and deposit it on top of the wire. As the solvent evaporated, a thin coating of substrate material would remain on the wire, making for a robust Buried Wire Gage. While applying the solvent droplet on the top of the wire, it was necessary to place a cap-like cover over the Gages to prevent any air currents or dust from disturbing the dissolved substrate. The syringe needle was passed through a hole on the side of the cover to get access to the wire. Even the smallest air current could leave ripples and waves on the substrate surface and any dust would contaminate the Gage, affecting its response characteristics in flow measurements.

In order to facilitate easy electrical connection to the Gage, the free end of the coaxial cable was soldered to a standard BNC-connector. The Gages were thus made ready for calibration. A typical instrument plug with finished Gages is shown in Fig. 4.

3.2 ANEMOMETER SYSTEM

A Constant Temperature Anemometer System was required for making measurements with Buried Wire Gages. The Anemometer system performed the following specific functions: (i) operated the sensor in the constant temperature mode at the desired operating temperature, (ii) provided an Overheat Reference Value which could be used as a measure of the local recovery temperature of 'wall' flow as indicated by the sensor, (iii) provided a Square Wave Test method to optimize the feedback circuit characteristics for a given sensor, and (iv) offered different functions for output signal conditioning.

The anemometer system used in the present experiments was the 16-Channel IFA 100 Intelligent Flow Analyzer system supplied by TSI Incorporated [Fig. 5].

3.2.1 CONSTANT TEMPERATURE OPERATION

The anemometer system, when set up to operate a Buried Wire Gage, would incorporate the Gage as one leg of a Wheatstone bridge circuit. The bridge circuit also included a built-in control resistor and a feed-back amplifier [Fig. 6]. The operating resistance appropriate to the desired sensor operating temperature could be dialed in by means of the control resistor. Constant temperature operation would begin when the anemometer system was set in 'RUN' mode. By passing a feed-back controlled current through the bridge, the Gage sensing element would be heated and maintained at the desired temperature. As a flow passed by the Gage, producing a cooling effect, the electrical resistance of the Gage sensing element would tend to drop. This decrease in the electrical resistance of the Gage would cause an unbalance in the bridge circuit. The feed-back amplifier would respond to the unbalance by providing an increased electrical current to the bridge circuit, thereby heating the element and bringing the bridge circuit back into balance. The current through the Gage sensing element then would be a measure of the flow. This current could be deduced from the voltage readings displayed on the front panel of the anemometer system.

It may be noted that, before setting the Gage operating resistance on the anemometer system, the resistance of the cable between the sensor and the anemometer system must be properly accounted for. The IFA 100 had a special feature which allowed entry of the cable resistance from a front panel keypad. This value would be automatically subtracted by the system display unit, before a resistance reading was flashed on the display panel. This meant that the sensor operating resistance would be directly displayed on the front panel.

3.2.2 OVERHEAT REFERENCE FUNCTION

The IFA 100 Anemometer System is equipped with a special feature in the 'STANDBY' operational mode, by which the resistance of the sensor could be deduced from the so-called 'Overheat Reference Value' and the control resistor (operating resistance) setting [Ref. 5]. This Overheat Reference Value displayed on the front panel would be an indication of the difference between the actual sensor resistance and the set operating resistance. With this feature, it would be possible to obtain the sensor resistance value while the sensor is submerged in flow. This resistance could then be converted to the local flow-induced 'recovery' temperature by using the sensor resistance-temperature law explained in Chapter 4.1.

Overheat Reference function could be selected by setting the anemometer system on 'STANDBY' - 'NULL DSPL'. The Overheat Reference Value [the 'NULL DSPL' reading on the front panel] represented the amount of off balance in the bridge circuit of the anemometer caused by the set operating resistance. Quantitatively, this off balance would be directly related to the 'OPERATE RES' control setting and the resistance of the Gage sensor. The resistance of the Gage could change due to ambient temperature changes or due to changes in flow conditions. As long as the 'OPERATE RES' control remained changed and the ambient temperature remained constant, the Overheat Reference Value would be proportional to the resistance of the Gage.

Although this Overheat Reference Function was built into the IFA 100 system, the operational manual did not provide a method for converting the Overheat Reference Values to actual resistance values. Consequently, a calibration of the Values had to be established, based on the anemometer bridge circuit parameters.

The governing equations for such calibration were derived as described below using simple electrical bridge circuitry principles [Fig. 6].

Electrical current values in the two halves of the bridge circuit are related by:

$$I_1 (R_1 + R_4) = I_2 (R_2 + R_3) \quad \dots(3)$$

The Overheat Reference Value is related to the unbalance in the bridge circuit and therefore may be expressed as:

$$(O/H) \sim I_1 R_1 - I_2 R_2 \quad \dots(4)$$

Total current supplied to the bridge circuit for the Overheat Reference Function is held invariant according to the design principles of the anemometer system. It follows that,

$$I_0 = I_1 + I_2 = \text{constant} \quad \dots(5)$$

For the specific bridge circuit contained in the IFA 100, the resistance values of Resistor-1 and Resistor-2 are each equal to 10 Ohms. The control resistor remains set at the desired Gage operating resistance when the Overheat Reference Function is selected on the anemometer system. It may be seen from Fig. 6 that, for the preset cable resistance and for the Gage sensor at the local temperature, the resistance values would be:

$$R_3 = R_s + R_{ca} \qquad R_4 = R_r + R_{ca} \quad \dots(6)$$

The equation for the Overheat Reference Value can then be obtained by combining Eqs.3-6 and defining a new anemometer system calibration proportionality constant termed the 'Overheat Reference Value Calibration Slope', (C/H):

$$(O/H) = (C/H) (R/F) \quad \dots(7)$$

with the Resistance Factor, (R/F) defined as

$$(R/F) = \frac{R_s - R_r}{20 + R_s + R_r + 2 R_{ca}} \quad \dots(8)$$

The Calibration Slope (C/H) in the above equation was determined from a special series of calibration measurements, for each channel of the anemometer system. The procedure consisted of connecting a Gage to each channel of the anemometer system, placing the Gages in a temperature controlled Environmental Test Chamber, and recording the Overheat Reference Values for different settings of operating resistance over a range of Test Chamber temperatures. It may be noted that the different Chamber temperatures provided different Gage resistance values, and thus assimilated a large number of calibration points that covered a wide range of the variables identified in Eqs.(7) and (8). These points are shown plotted in Fig. 7 for the sixteen channels of the Anemometer System.

At a first glance, the spread among different points in Fig. 7 may look like a high level of scatter in calibration measurements, but it must be noted that the spread actually represents the different Calibration Slope values among the sixteen channels of the anemometer system and does not necessarily reflect the amount of scatter in the calibration measurements.

Calibration points corresponding to each channel of the anemometer system were individually grouped together, and a least squared line fit was determined to finally obtain the slope represented by those points. The Calibration Slope (C/H) values obtained for the different channels are given in Fig. 7.

Next, in an effort to demonstrate the validity of the Calibration Slope (C/H) values for a larger range of Resistance Factor values, calibration measurements were extended for a few channels using different sensors, in the form of hot wire probes. The results of these calibrations are shown in Fig. 8, from which it is clear that the Calibration Slope values remain unaltered for the entire range of Resistance Factors values.

3.2.3 SQUARE WAVE TEST TECHNIQUE

An important part of the operation of the constant temperature anemometer system was the adjustment of the different controls to obtain a high dynamic response to possible fluctuations in flow past the sensor. The IFA 100 Anemometer system had a special feature for introducing a square-wave test signal into the anemometer bridge circuit. Response of the system could be visually verified on an oscilloscope and also used as a basis to optimize the frequency response of the anemometer system, for any given sensor. The amplitude and frequency of the test signal could be continuously varied. Optimization of the response was achieved by proper adjustments of the BRIDGE COMPENSATION AND CABLE COMPENSATION controls on the Anemometer System, as described in the operational manual [Ref. 5]. A typical optimized response is shown in Fig. 6. Excellent response to flow fluctuations at the sensor would be achieved if the pulse is short and without undershoot. The cutoff frequency for the anemometer system-sensor combination may then be evaluated from the time interval t' which is defined as the time from the start of the pulse until the pulse has decayed to 3% of its maximum value.

$$\text{CUTOFF FREQUENCY} = \frac{1}{1.5 t'}$$

3.2.4 OUTPUT SIGNAL CONDITIONING

The output signal of the Anemometer System could be conditioned for convenience of further interpretation. The anemometer system was equipped with a signal conditioner that could offset, amplify, and filter the output signal before transmitting to external signal acquisition and processing equipment. The signal conditioner featured keypad entry for selective digital display of offset, gain, and filter values for each channel.

3.3 ENVIRONMENTAL TESTING CHAMBER

The calibration procedure for determining the Conduction Loss Factor 'A' of Eq.(2) required a constant temperature no-flow environment, in which the Gages could be placed and connected via cables to the anemometer system. Such an environment was available in an existing Environmental Test Chamber. The temperature within the chamber could be set for any value within the range of -73.0 deg.C to +315.0 deg.C, and that temperature would be maintained to within ± 0.1 deg.C. In order to achieve temperatures below ambient, the chamber used liquid nitrogen as the coolant.

4. CALIBRATION PROCEDURE

The governing equations for the Buried Wire Gage Technique, explained in Chapter 2 of this report, called for determination of the calibration constants A and B. In addition, the local flow temperatures [such as the 'wall flow recovery' temperature] needed to be derived from measurements of Gage resistance values [see Eq.(2)]. A calibration procedure was therefore required to determine the Gage resistance temperature law as well as the factors A and B. The calibration procedure thus involved three steps, described in the following paragraphs.

4.1 GAGE RESISTANCE TEMPERATURE LAW

The first step of the calibration procedure was determination of the Temperature Coefficient of Resistance and the standard resistance value, which define the Gage resistance temperature law as given below.

$$R = R_{std} [1 + \alpha (T - T_{std})] \quad \dots(9)$$

To determine these calibration constants, each Gage was brought to several chosen temperatures in the Environmental Testing Chamber. The resistance of each gage was measured, using the null-balance feature of the Anemometer System, at each chosen temperature. The relation between temperature and

resistance was basically linear, but to account for the effects of scatter, a least-squares error line fit was made for the measured values of each Gage. The least-squares fit was then substituted into Eq.(9) to obtain the desired constants, namely Temperature Coefficient of Resistance and the 'standard' resistance at 20 deg.C.

4.2 CONDUCTION LOSS FACTOR 'A'

The Conduction Loss Factor, A, shown in Eq.(2), represents the amount of heat lost by thermal conduction to the substrate, and could be conveniently determined by constant temperature operation of the Gage in a no-flow environment. The Environmental Test Chamber was an ideal choice for that purpose. An added advantage with the Chamber was that the conduction loss measurements could be made at several 'ambient' temperatures to obtain a reasonably large sample of data on each Gage. Because still-air is a very poor conductor, the amount of heat lost to the air through natural convection, conduction, or radiation could be considered negligible. Therefore, any heat loss encountered by the Gage was attributed to thermal conduction into the substrate.

The Anemometer Bridge Circuit Voltage, necessary to keep the anemometer bridge circuit balanced, may be related to the Conduction Loss Factor by the following set of equations [Ref. 5]:

$$A = \frac{h_0}{k_{sub} b (T_s - T_0)} \quad \dots(10)$$

$$h_0 = \frac{V_0^2 R_s}{(10 + R_s + R_{ca}^2)} \quad \dots(11)$$

$$T_s - T_0 = \frac{R_s - R_0}{\alpha R_{std}} \quad \dots(12)$$

It may be noted that Eq.(11) is specific to the IFA 100 Anemometer System used in the 'BLASTANE' project. This anemometer system has a series resistance of 10 Ohms in each half of the bridge circuit.

The thermal conductivity of the substrate material, in the present case polystyrene, was calculated from [temperature expressed in deg.C]:

$$k_{\text{sub}} = 0.10796 + 0.000168(T - 20) \quad ; [W/m.degC] \quad \dots(13)$$

It may be noted that the excess temperature, as depicted by Eq.(12), was determined from the set operating resistance value, and the 'cold/ambient' resistance value which was derived by using the Overheat Reference function of the anemometer system [see Eqs.(7) and (8)]. The Overheat Reference Value for this purpose was obtained by setting the anemometer system temporarily on the 'STANDBY - NULL DSPL' mode prior to bringing it to the 'RUN' mode for obtaining the voltage value.

4.3 EQUIVALENT LENGTH FACTOR 'B'

Although the present experiments did not include determinations of the Equivalent Length Factor values, the procedure for such determinations is identified below for the sake of completeness of this discussion on calibration procedure.

The Equivalent Length Factor 'B' in Eq.(2) represents the effective length of the Gage sensor in terms of the heat transfer process. This factor must be determined from measurements taken in a flow of known wall shear stress. The BLASTANE Calibration Tube is expected to provide such a known flow [Ref. 6]. Because of the ample length of the Calibration Tube, the wall shear stress values in the flow at the calibration section which accommodates the Gages may be simply evaluated from the well-known 'fully developed pipe flow' equation:

$$\tau_w = 0.25 d p' \quad \dots(14)$$

The voltage V, measured on the anemometer system, while the Gage sensor placed in flow is operated from it, is related to the shear stress through Eqs.(1) and (2). The Equivalent Length Factor values may be determined from the measurements by solving for 'B' in Eq.(1), for the known shear stress values deduced from Eq.(14).

Eqs.(1) and (2) are reproduced below for quick reference:

$$\tau_w = 1.9 \frac{\mu^2}{\rho (Pr)} \frac{Nu^3}{(B d)^2} - 0.2778 \frac{(B d)(p')}{Nu} \quad \dots(15)$$

where,

$$Nu = \frac{h}{k_b (T_s - T_r)} - (A) \frac{k_{sub}}{k} \quad \dots(16)$$

$$h = \frac{V^2 R_s}{(10 + R_s + R_{ca})^2} \quad \dots(17)$$

The additive constant '10' in the denominator of Eq.(17) is the value of the resistance in series with the sensor in the anemometer bridge circuit. The different variables in Eqs.(15) to (17) may be derived as follows:

T_s : calculated from R_s , using Eq.(9). ;[deg.C]

T_r : calculated from R_r , using Eq.(9). R_r is obtained from Eqs.(7) and (8), for the Overheat Reference Value (O/H) obtained from the anemometer system with controls set at the operating resistance and operational mode set on 'STANDBY'-'NULL DSPL', flow passing over the Gage.

μ : calculated for the operating temperature[in deg.C] from standard air property relationships:

$$= .00000188 \left(\frac{273 + T_s}{300} \right)^{0.76} \quad ;[\text{kg.sec/sq.m}].$$

k_{sub} : calculated for the flow recovery temperature {in deg.C}
 $= 0.10796 + 0.000168(T_r - 20) \quad ;[\text{W/m.degC}].$

k_s : calculated for Gage operating temperature {in deg.C}
 $= 0.02615 + 0.0000759 (T_s - 27) \quad ;[\text{W/m.degC}].$

5. RESULTS AND DISCUSSION

In all, a total of 121 Buried Wire Gages built into 23 BLASTANE Instrument Plugs were calibrated using the IFA 100 Anemometer system and the Environmental Test Chamber. The calibrations of Gage Resistance versus Temperature were performed for Test Chamber temperature settings of 60, 50, 40, 35, 20, 10 and 0 deg.C. A typical result of this phase of calibration appears in Fig. 9.

The calibrations of Conduction Loss Factor were performed for Operating Resistance settings corresponding to 60 deg.C and 50 deg.C, and Test Chamber settings of 35 deg.C and 5 deg.C. In some cases, calibrations were also made with the Test Chamber controls turned off and the Gages open to room ambient temperature.

It may be relevant to note here that, during earlier calibration experiments, a rather high level of scatter was observed in the measurements of Conduction Loss Factors. This was subsequently attributed to the circulating flow produced by the Test Chamber circulation fans which were intended to help maintain a uniform temperature across the entire volume of the Chamber. Although the flow helped achieve a uniform temperature environment, it had the undesirable effect of causing convective heat transfer from the Gages and thus introducing a high level of scatter among different measurements performed at different Chamber temperature settings. This problem was rectified by turning the circulation fans off for a short duration while voltage readings were taken on the Anemometer System.

The expected linear relationship between resistance and temperature for the Gage sensor was borne out by the calibrations, as typically shown in Fig. 9. The 'standard' resistance value and the Temperature Coefficient of Resistance value for each Gage were determined from this line fit and are listed in Table 1.

The Conduction Loss Factor calibrations for the different Gages were found to be typical to those shown in Fig. 10. The scatter that appears in the different calibration points of the same Gage is of the order of 3% peak to peak. This level of scatter is comparable to what was found in previous experiments performed by Murthy and Rose [Ref. 3], who used similar Gages. The average Conduction Loss Factor values for the different Gages appear in Table 1.

6. CONCLUDING REMARKS

Buried Wire Gages were developed for use in the Boundary Layer Apparatus for Subsonic and Transonic flow Affected by Noise Environment ('BLASTANE'). These Gages were of a new type and special care had to be taken to build reliable and robust Gages. Detailed studies were undertaken to identify a proper fabrication method for making reliable Gages.

Starting from the governing equations of fluid flow and the the analogy between momentum and heat transfer processes, a carefully thoughtout calibration procedure was evolved to render the Gages useful as reliable flow measuring devices when operated from a constant temperature anemometer system. The calibration procedure was identified to consist of three distinct steps to determine the three calibration factors, namely Temperature Coefficient of Resistance, Conduction Loss Factor, and Equivalent Length Factor.

Several stages in the calibration procedure called for determination of the unheated ('cold') sensor element, ^{resistance} so that this resistance would then become a measure of the local flow temperature at the wall. This resistance determination could be conveniently accomplished from a special feature called the 'Overheat Reference Function' of the IFA-100 Anemometer system used in the present experiments. However, the supplier of the Anemometer System had not provided any calibration for this function. In order to arrive at such a calibration, the governing equations of the anemometer bridge circuit were rearranged to identify the proper correlating variables in terms of the circuit elements. This led to the definition of a new parameter called 'Resistance Factor' to represent the 'cold' resistance in the calibration law. A series of measurements were then made with Buried Wire Gages as sensors to derive the calibration constant for the functional relationship between the Overheat Reference Value and the newly defined 'Resistance Factor'. The measurements were repeated for each channel of the Anemometer System to obtain the corresponding calibration constant. Finally, validity of this calibration law for a wide range of resistance values was demonstrated by a series of measurements with different sensor elements.

Although the Gages had been fabricated with great care, the calibrations differed significantly from one Gage to the other. This, in any case, is typical of this type of flow measuring instrumentation which measures fluid flow parameters through the analogy between momentum transfer and heat transfer mechanisms. Several calibrations have been performed for each Gage to obtain an appreciation of the uncertainties in the calibration equipment and method. Scatter among the different calibrations of each Gage appears to be within acceptable limits and typical to measurements made previously with similar Gages. Typical results of the calibrations are presented in the different Figures.

7. ACKNOWLEDGMENTS

The authors wish to thank Mr. Fred R. Lemos for his sincere and persistent efforts during the development of a proper method to fabricate the Buried Wire Gages used in the present series of calibration experiments. Thanks are also due to Miss. Anne-Marie Salmi and Mr. Ken Gee who performed much of the calibration measurements.

8. REFERENCES

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TABLE-1 : SUMMARY OF BURIED WIRE GAGE CALIBRATIONS

GAGE NO.	RESISTANCE AT 20 DEG.C (ohms)	TEMPERATURE COEFF OF RESISTANCE (/deg.C)	RESISTANCE AT 60 DEG.C (ohms)	CONDUCTION LOSS FACTOR.
1	5.627	0.00370	6.468	1.434
2	5.566	0.00373	6.403	1.520
3	5.811	0.00376	6.693	1.524
4	5.702	0.00377	6.577	1.469
5	5.835	0.00371	6.701	1.498
6	5.668	0.00375	6.523	1.399
7	5.675	0.00372	6.524	1.472
8	5.469	0.00374	6.297	1.406
9	5.512	0.00377	6.350	1.533
10	5.371	0.00377	6.190	1.542
11	5.506	0.00371	6.323	1.429
12	5.522	0.00373	6.346	1.448
13	5.587	0.00374	6.424	1.473
14	5.849	0.00375	6.734	1.497
15	5.589	0.00372	6.418	1.459
16	5.634	0.00382	6.514	1.422
17	5.841	0.00380	6.753	1.479
18	5.496	0.00383	6.361	1.481
19	5.528	0.00383	6.403	1.441
20	5.658	0.00382	6.545	1.488
21	5.669	0.00382	6.547	1.488
22	5.619	0.00383	6.495	1.432
23	5.590	0.00374	6.437	1.390
24	5.543	0.00379	6.394	1.530
25	5.569	0.00384	6.440	1.329
26	5.276	0.00375	6.083	1.444
27	5.592	0.00374	6.437	1.418
28	5.417	0.00381	6.255	1.425
29	5.649	0.00377	6.514	1.387
30	5.355	0.00377	6.175	1.521
31	5.561	0.00373	6.401	1.426
32	5.645	0.00384	6.521	1.418
33	5.345	0.00372	6.152	1.353
34	5.534	0.00378	6.379	1.473
35	5.582	0.00368	6.433	1.360
36	5.464	0.00385	6.319	1.465
37	5.481	0.00411	6.383	1.640
38	5.716	0.00379	6.597	1.463
39	5.347	0.00382	6.182	1.407
40	5.533	0.00376	6.375	1.416

TABLE-1 (Continued)

GAGE NO.	RESISTANCE AT 20 DEG.C (ohms)	TEMPERATURE COEFF OF RESISTANCE (/deg.C)	RESISTANCE AT 60 DEG.C (ohms)	CONDUCTION LOSS FACTOR.
41	5.849	0.00379	6.753	1.632
42	5.897	0.00374	6.788	1.572
43	5.517	0.00370	6.342	1.579
44	5.684	0.00368	6.531	1.586
45	5.476	0.00369	6.290	1.537
46	5.520	0.00374	6.351	1.573
47	5.540	0.00370	6.367	1.593
48	5.711	0.00363	6.547	1.560
49	5.768	0.00356	6.593	1.558
50	5.542	0.00371	6.367	1.627
51	5.540	0.00366	6.354	1.537
52	5.902	0.00378	6.796	1.586
53	5.724	0.00376	6.603	1.652
54	5.764	0.00369	6.625	1.631
55	6.089	0.00377	7.021	1.619
56	5.731	0.00376	6.607	1.643
57	5.368	0.00364	6.156	1.490
58	5.684	0.00365	6.519	1.571
59	5.569	0.00365	6.390	1.516
60	5.811	0.00379	6.703	1.663
61	5.819	0.00372	6.678	1.547
62	5.553	0.00372	6.385	1.567
63	5.930	0.00374	6.825	1.610
64	5.590	0.00373	6.429	1.567
65	5.464	0.00364	6.263	1.585
66	5.992	0.00371	6.878	1.665
67	5.832	0.00380	6.726	1.624
68	5.761	0.00371	6.625	1.586
69	5.987	0.00367	6.877	1.538
70	5.412	0.00368	6.215	1.509
71	5.447	0.00374	6.270	1.549
72	5.817	0.00367	6.675	1.556
73	5.831	0.00368	6.698	1.591
74	5.597	0.00370	6.427	1.601
75	5.751	0.00369	6.603	1.622
76	5.242	0.00374	6.031	1.588
77	5.600	0.00363	6.416	1.416
78	5.720	0.00372	6.573	1.535
79	5.641	0.00374	6.491	1.558
80	5.513	0.00382	6.356	1.500

TABLE-1 (Continued)

GAGE NO.	RESISTANCE AT 20 DEG.C (ohms)	TEMPERATURE COEFF OF RESISTANCE (/deg.C)	RESISTANCE AT 60 DEG.C (ohms)	CONDUCTION LOSS FACTOR.
81	5.635	0.00371	6.479	1.477
82	5.752	0.00360	6.588	1.457
83	5.464	0.00372	6.286	1.486
84	5.766	0.00372	6.631	1.610
85	5.358	0.00359	6.155	1.342
86	5.540	0.00376	6.388	1.480
87	5.734	0.00373	6.601	1.495
88	5.651	0.00386	6.538	1.445
89	5.441	0.00377	6.271	1.435
90	5.716	0.00367	6.576	1.429
91	5.651	0.00377	6.508	1.559
92	5.733	0.00383	6.617	1.454
93	5.633	0.00375	6.481	1.432
94	5.641	0.00381	6.510	1.496
95	5.431	0.00383	6.268	1.524
96	5.702	0.00380	6.576	1.498
97	5.675	0.00377	6.545	1.465
98	5.890	0.00376	6.779	1.508
99	5.643	0.00372	6.488	1.483
100	5.611	0.00388	6.479	1.611
101	5.883	0.00372	6.757	1.546
102	5.824	0.00374	6.694	1.557
103	5.733	0.00381	6.606	1.554
104	5.815	0.00389	6.721	1.670
105	4.066	0.00365	4.660	1.704
106	3.815	0.00369	4.378	1.679
107	3.936	0.00377	4.529	1.727
108	5.543	0.00368	6.359	1.559
109	5.309	0.00381	6.117	1.480
110	5.540	0.00390	6.403	1.506
111	5.486	0.00370	6.298	1.494
112	4.033	0.00357	4.609	1.994
113	3.725	0.00362	4.265	1.676
114	3.548	0.00372	4.075	1.694
115	5.599	0.00378	6.446	1.472
116	5.639	0.00379	6.494	1.419
117	5.658	0.00380	6.518	1.494
118	5.615	0.00378	6.462	1.468
119	3.759	0.00360	4.301	1.580
120	3.577	0.00364	4.099	1.628
121	3.846	0.00374	4.421	1.754

SCHEMATIC OF BURIED WIRE GAGE TECHNIQUE

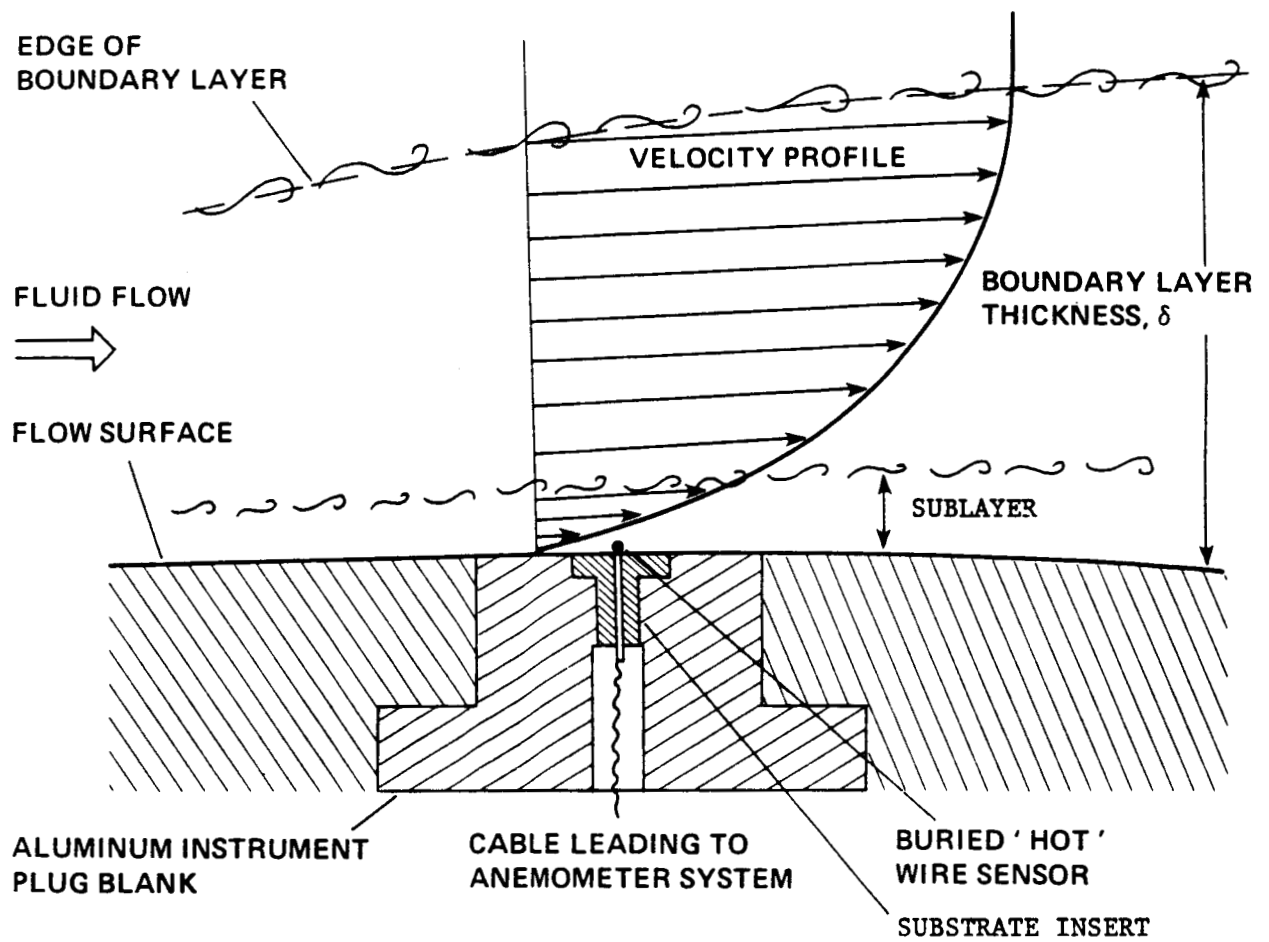
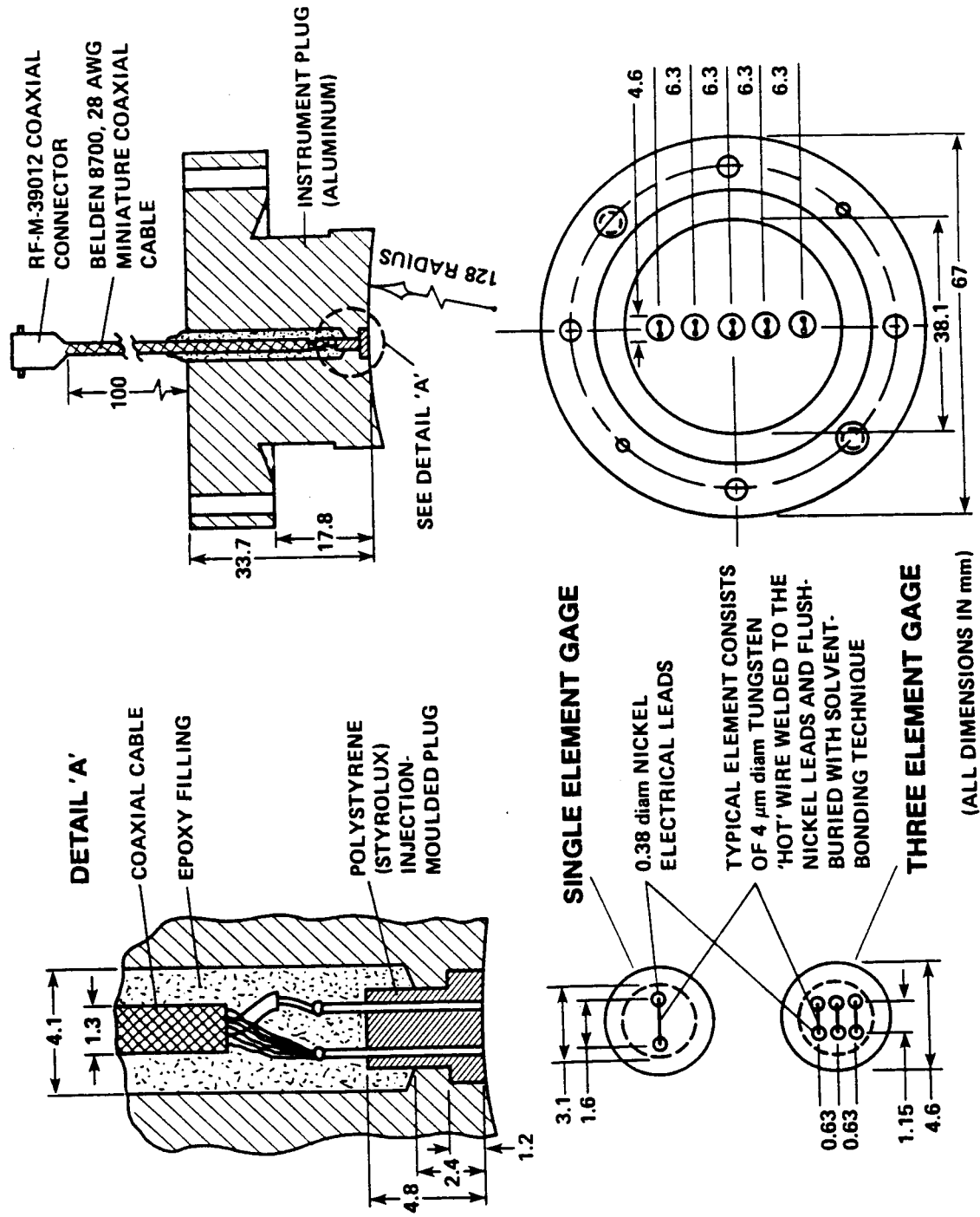


Figure 1

BURIED WIRE GAGE ELEMENTS IN INSTRUMENT PLUGS OF BOUNDARY LAYER APPARATUS FOR SUBSONIC AND TRANSONIC FLOWS AFFECTED BY NOISE ENVIRONMENT



MURTHY

Figure 2

SUBSTRATE INSERT FABRICATION STAGES

CYLINDRICAL
ADAPTERS TO
POSITION
ELECTRICAL LEADS
DURING INJECTION
MOLDING

CYLINDRICAL
ADAPTERS
WITH ELECTRICAL
LEADS

SUBSTRATE
INSERT AFTER
POLISHING

INJECTION-
MOLDED
SUBSTRATE
BLANK, STILL
ATTACHED TO
CYLINDRICAL
ADAPTERS

INJECTION-
MOLDED
SUBSTRATE
BLANK

SUBSTRATE
INSERT WITH
CABLE LEADS

SUBSTRATE INSERT AT DIFFERENT STAGES OF FABRICATION

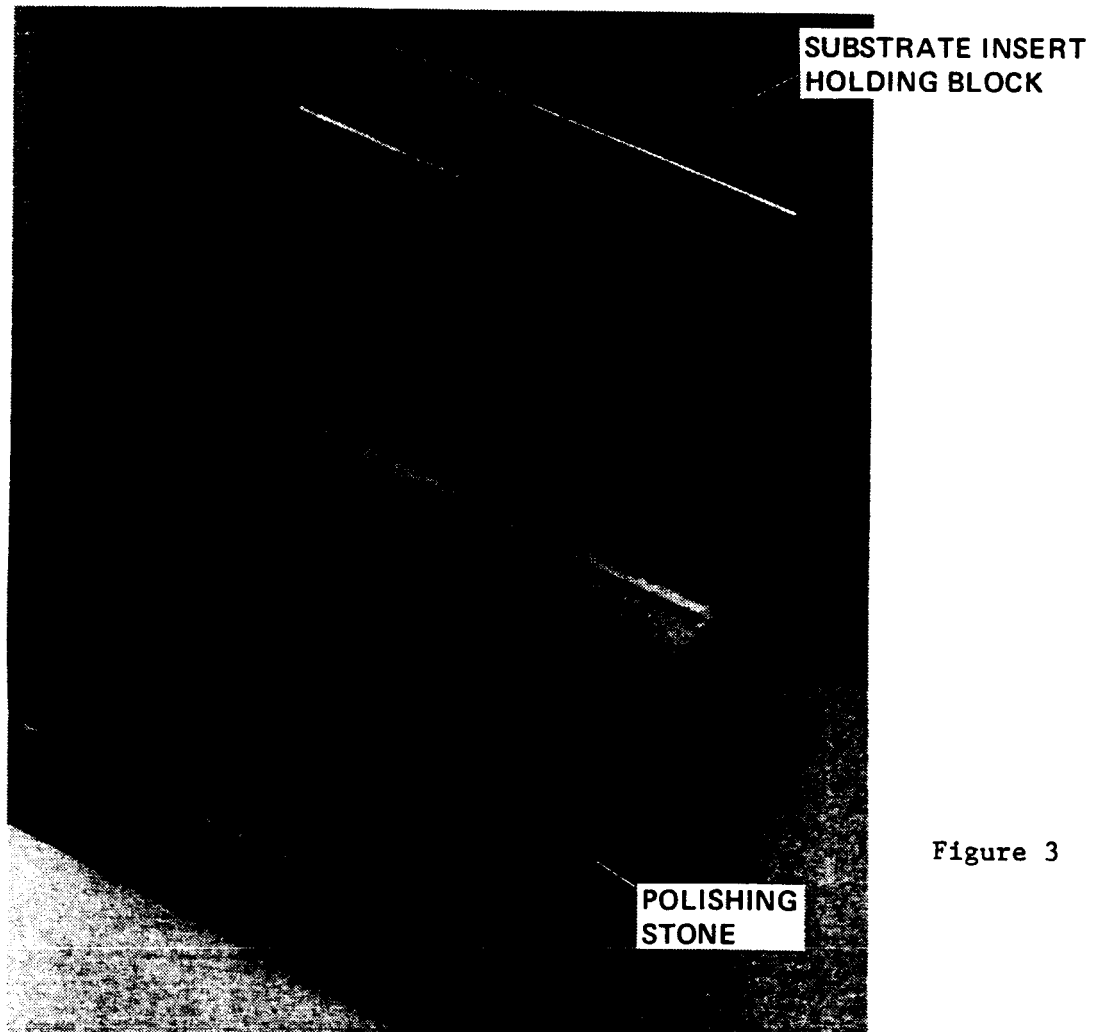
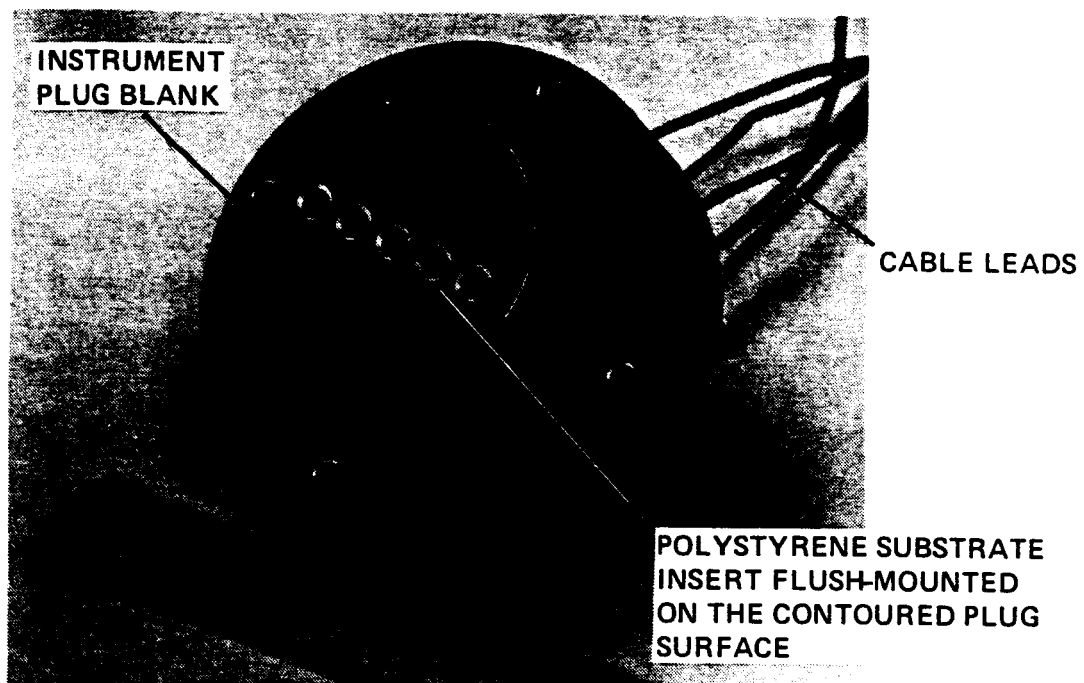


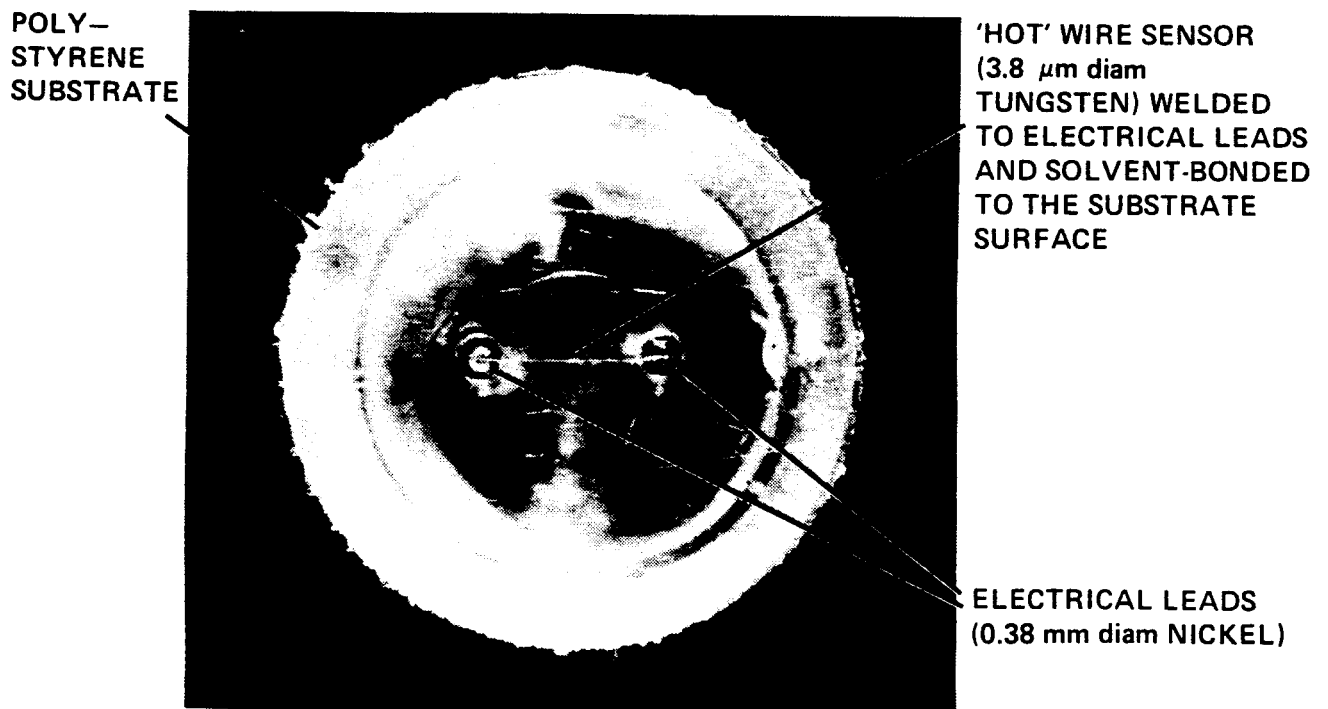
Figure 3

SUBSTRATE-HOLDER AND POLISHING STONE

INSTRUMENT PLUG BLANK WITH BURIED WIRE GAGES



PLUG BLANK WITH 5 GAGES

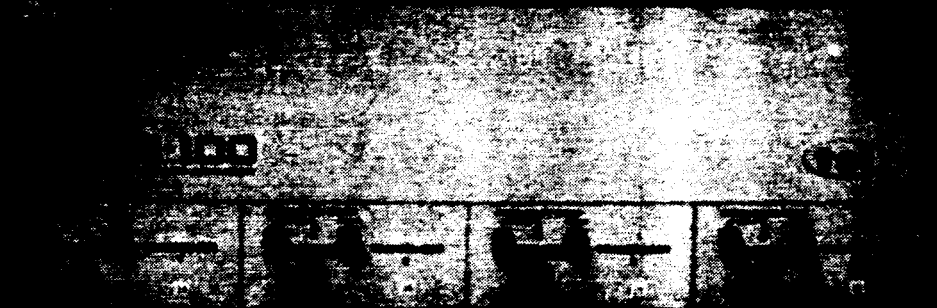
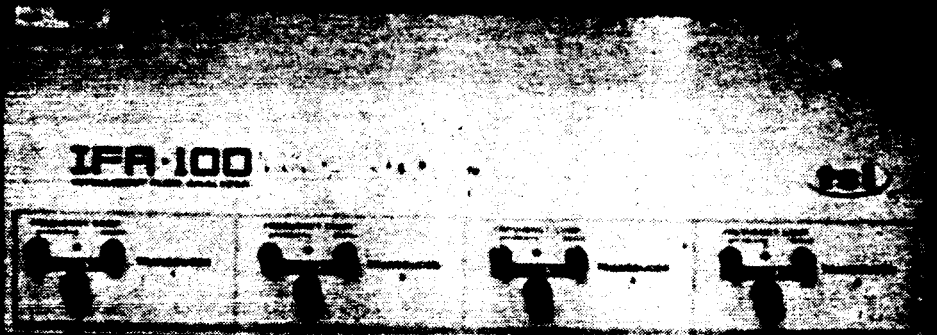
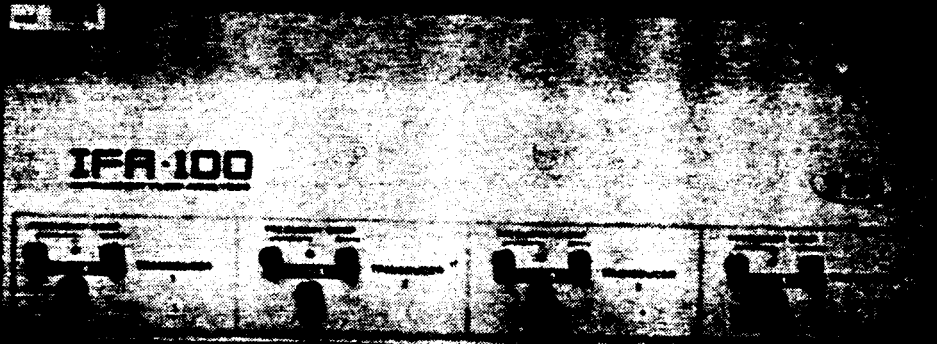
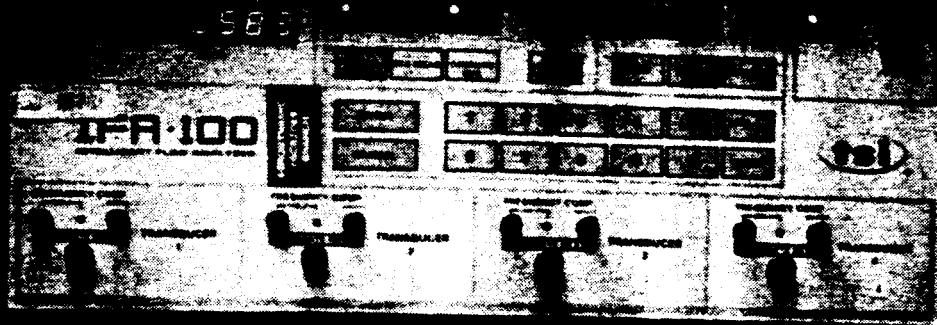


MAGNIFIED VIEW OF A BURIED WIRE GAGE

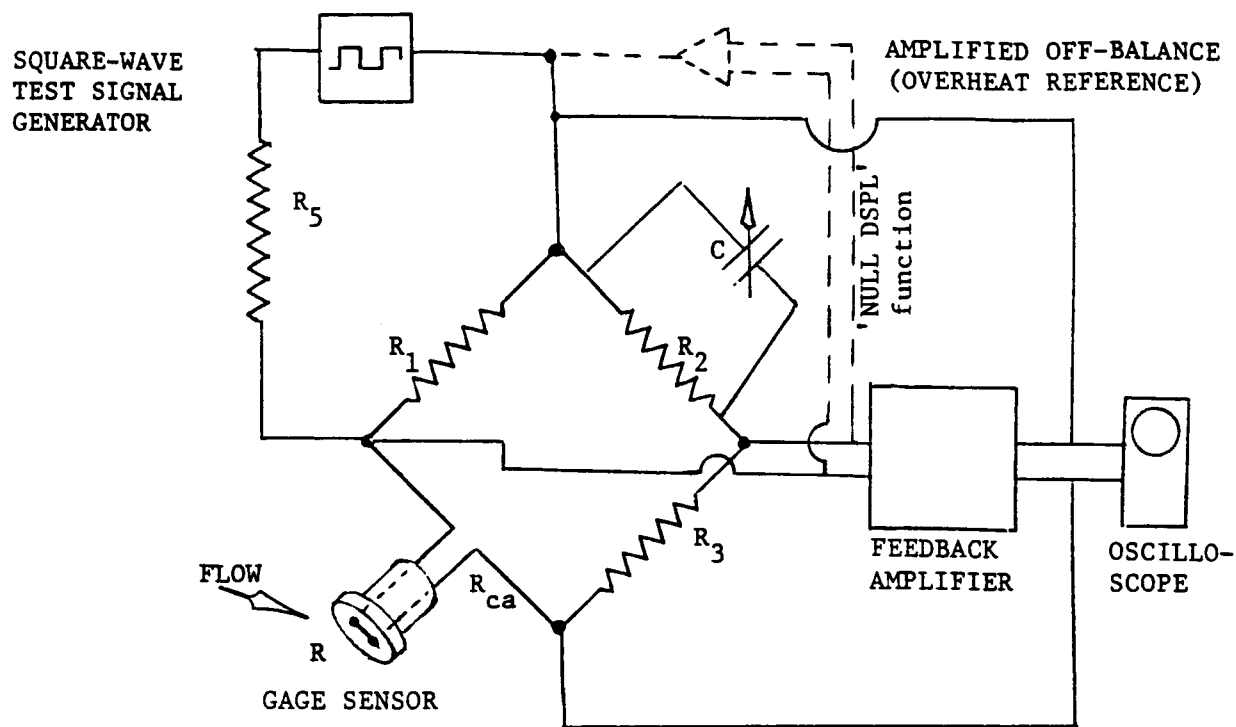
Figure 4

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16 - CHANNEL CONSTANT TEMPERATURE ANEMOMETER SYSTEM



ANEMOMETER BRIDGE AND TEST SIGNAL CIRCUIT

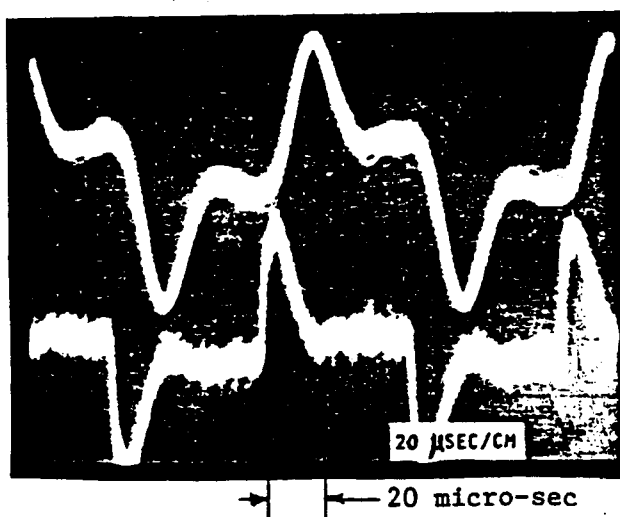


(a) ANEMOMETER BRIDGE CIRCUIT AND FEEDBACK SYSTEM

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UNFILTERED
SIGNAL

FILTERED
SIGNAL

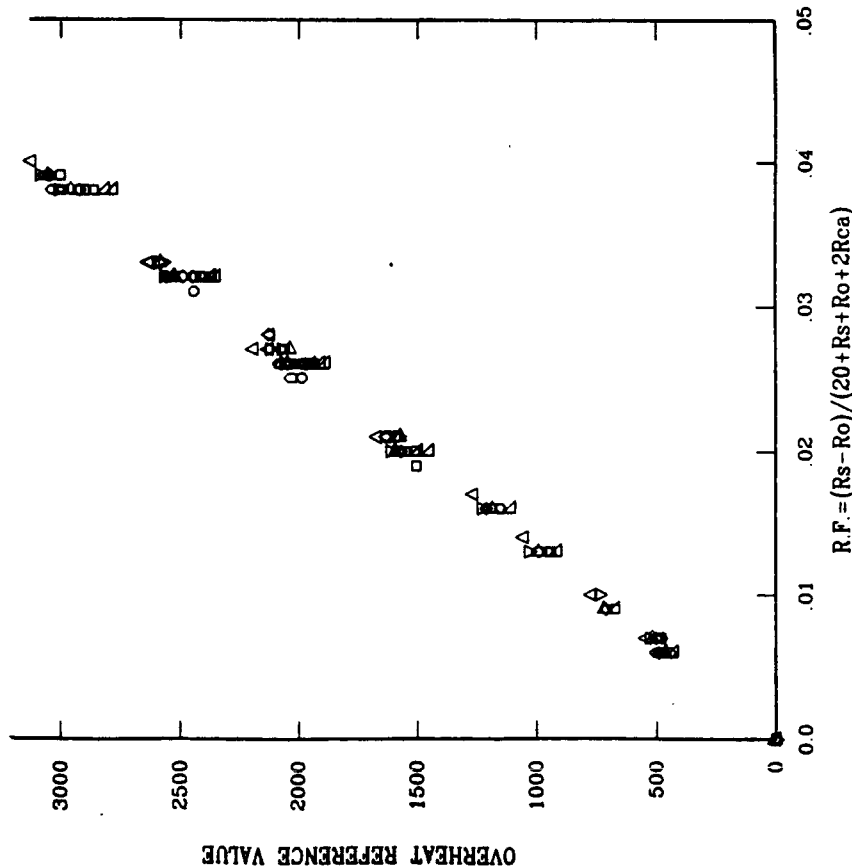


(b) OSCILLOSCOPE TRACE OF SQUARE WAVE TEST SIGNAL RESPONSE

CALIBRATION OF OVERHEAT REFERENCE VS RESISTANCE FACTOR ANEMOMETER CHANNELS 1 THRU 8; Gage Sensors, 1-16-86

SYMBOL	ANEMOMETER CHANNEL NO.	OVERHEAT REF CALIB SLOPE
○	1	77113
◇	2	76297
△	3	77410
□	4	78667
◇	5	73637
△	6	79329
□	7	78531
△	8	78131

NOTE: THE DIFFERENT SYMBOLS REFER TO DIFFERENT CHANNELS AND THEREFORE CORRESPOND TO DIFFERENT LINE FITS. THE SPREAD OF POINTS ALMOST ENTIRELY REFLECTS THE DIFFERENT LINE FITS.



CALIBRATION OF OVERHEAT REFERENCE VS RESISTANCE FACTOR ANEMOMETER CHANNELS 9 THRU 16; Gage Sensors, 1-16-86

SYMBOL	ANEMOMETER CHANNEL NO.	OVERHEAT REF CALIB SLOPE
○	9	75451
◇	10	78348
△	11	77804
□	12	78578
◇	13	77386
△	14	75497
□	15	77414
△	16	80707

NOTE: THE DIFFERENT SYMBOLS REFER TO DIFFERENT CHANNELS AND THEREFORE CORRESPOND TO DIFFERENT LINE FITS. THE SPREAD OF POINTS ALMOST ENTIRELY REFLECTS THE DIFFERENT LINE FITS.

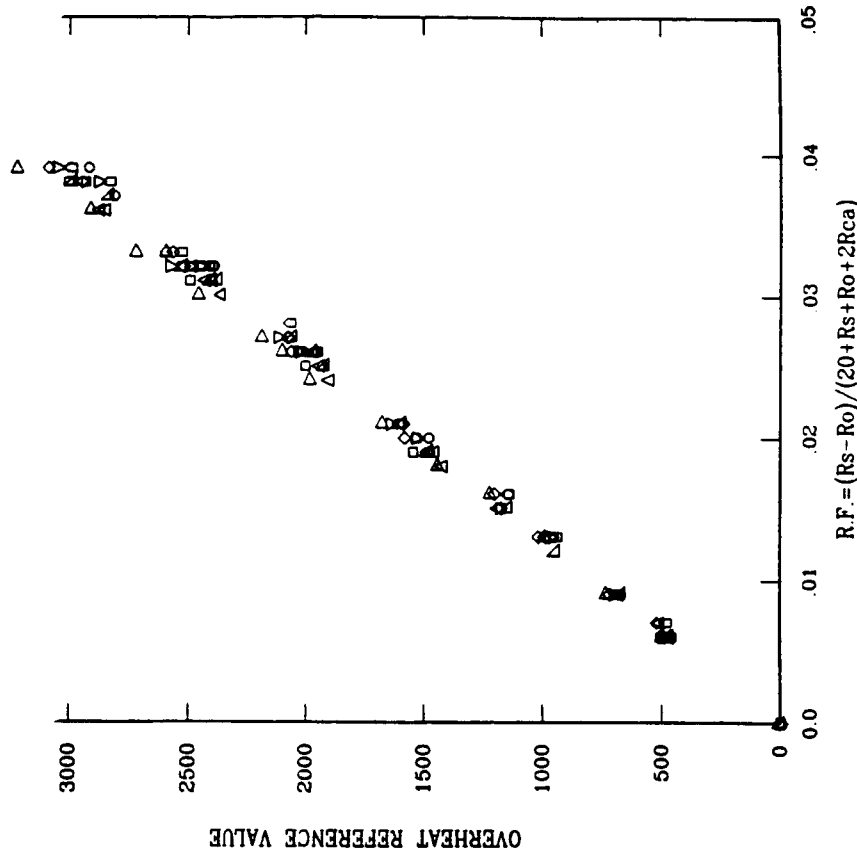
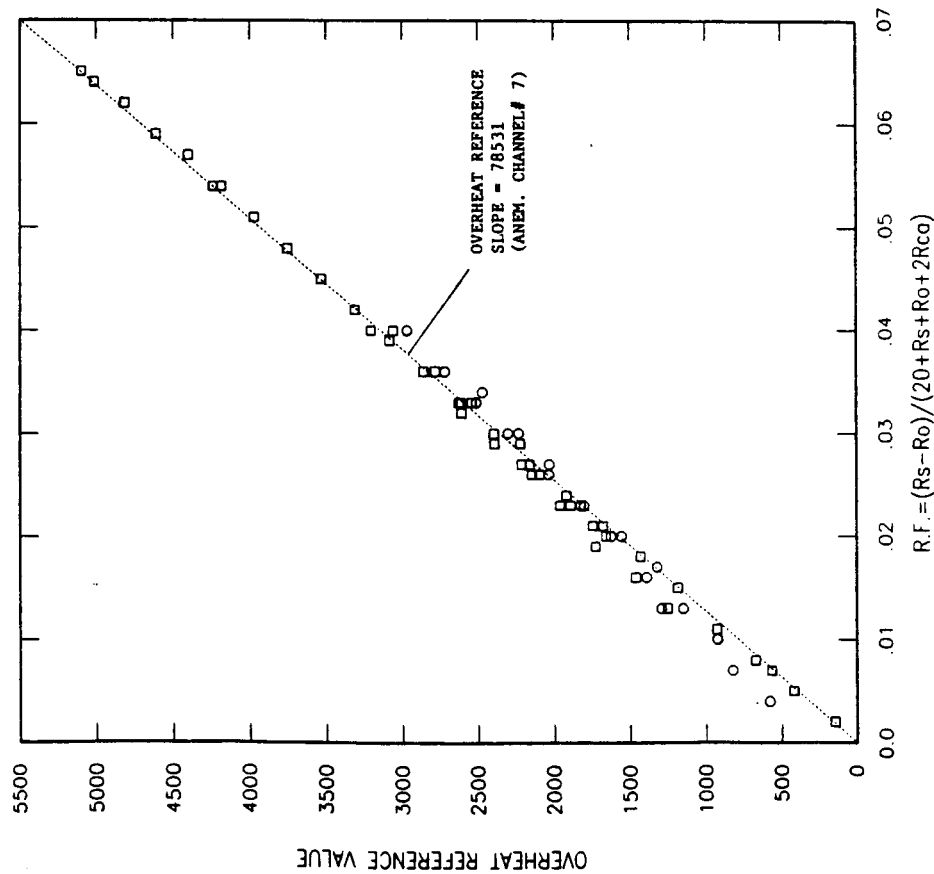


Figure 7

CALIBRATION OF OVERHEAT REFERENCE VS. RESISTANCE FACTOR
HOT WIRE PROBES : 9-9-85 ; Rs=Op Res ; Ro=Cold Res

SYMBOL	SENSOR	TEMP COEFF OF RES., $\alpha/\text{deg.C}$	RESISTANCE(Ohm)	
			AT 20 deg.C	AT 20 deg.C
○	PROBE-1	0.48	4.26	
□	PROBE-2	0.49	4.24	



CALIBRATION OF OVERHEAT REFERENCE VS RESISTANCE FACTOR
HOT-WIRE PROBES : 11-7-85 ; Rs=Op Res ; Ro=Cold Res

SYMBOL	SENSOR	TEMP COEFF OF RES., $\alpha/\text{deg.C}$	RESISTANCE(Ohm)	
			AT 20 deg.C	AT 20 deg.C
○	PROBE-1	0.48	4.26	
□	PROBE-2	0.49	4.24	

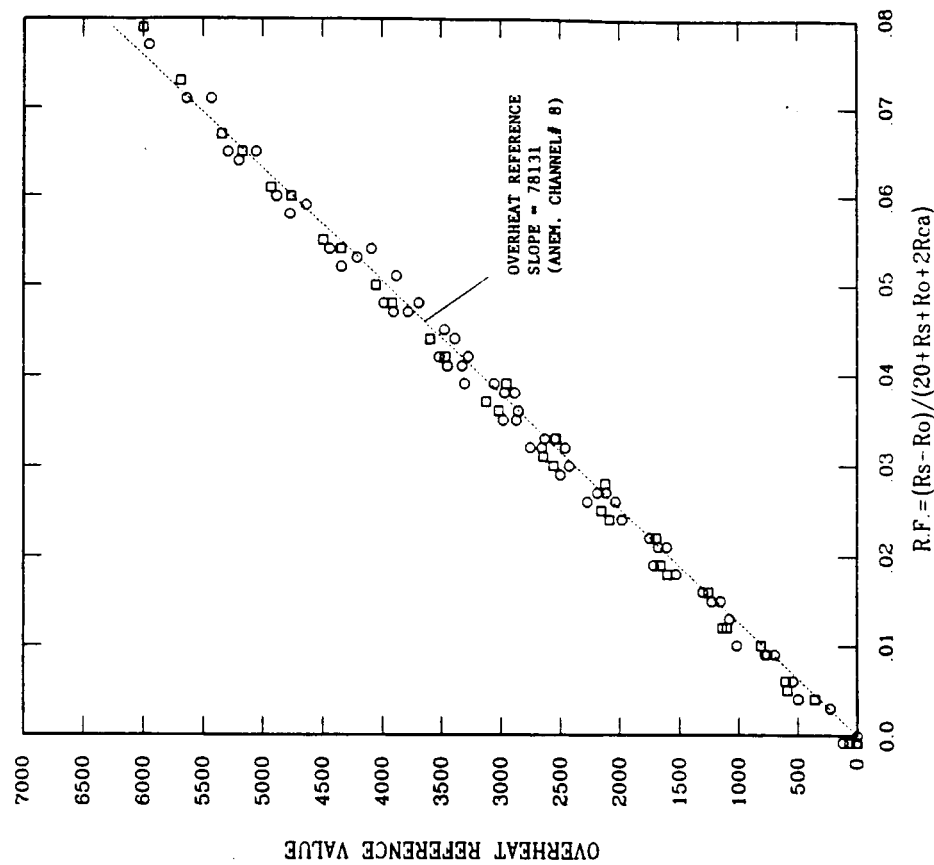
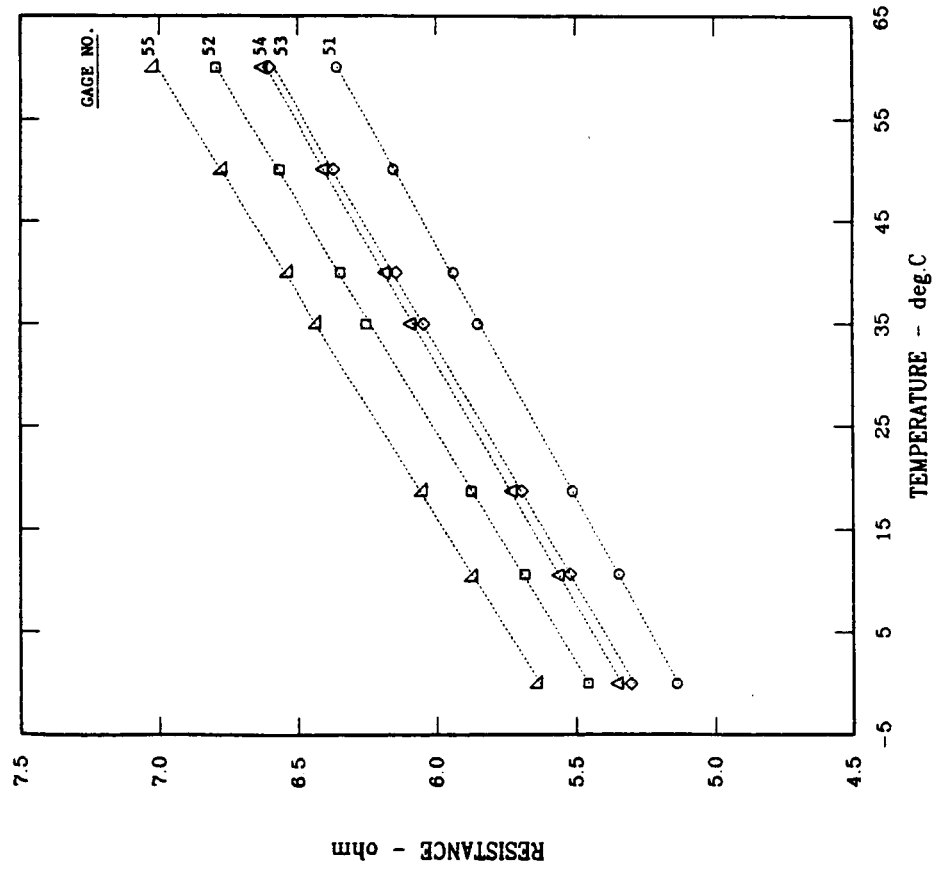


Figure 8

RESISTANCE vs TEMPERATURE CALIBRATION FOR GAGES
BURIED WIRE GAGES #51 TO #55; Instr. Plug# 11; 10-24-85



RESISTANCE vs TEMPERATURE CALIBRATION FOR GAGES
BURIED WIRE GAGES #101 TO #107; Instr. Plug #21; 7-21-86

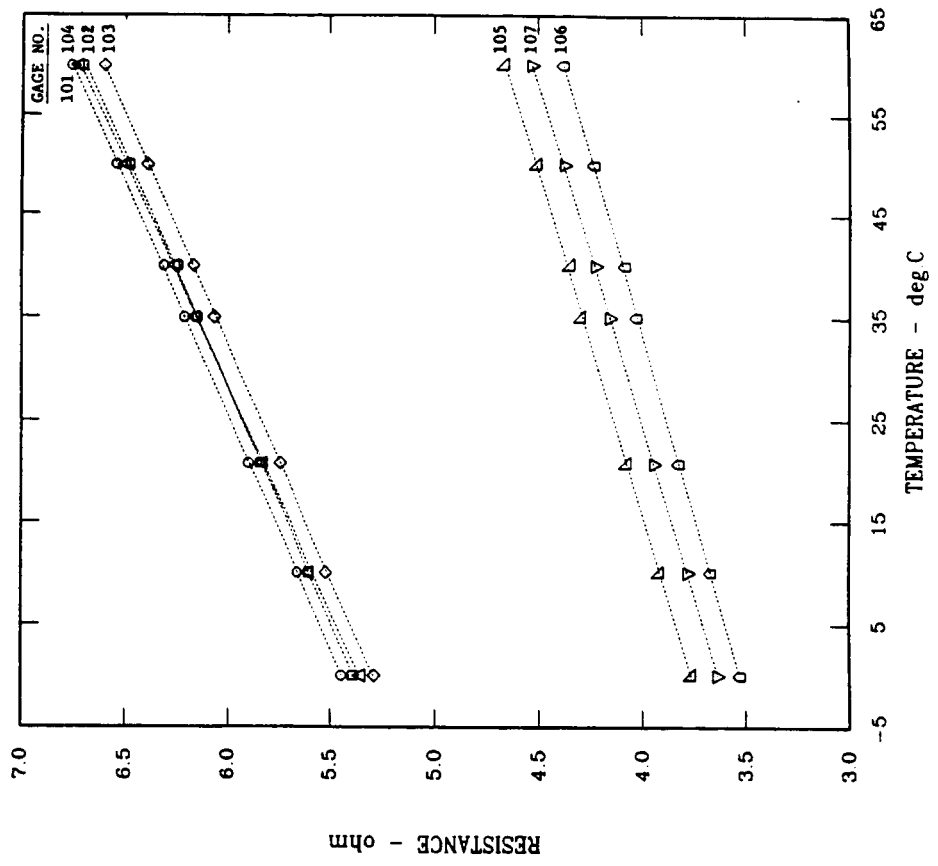
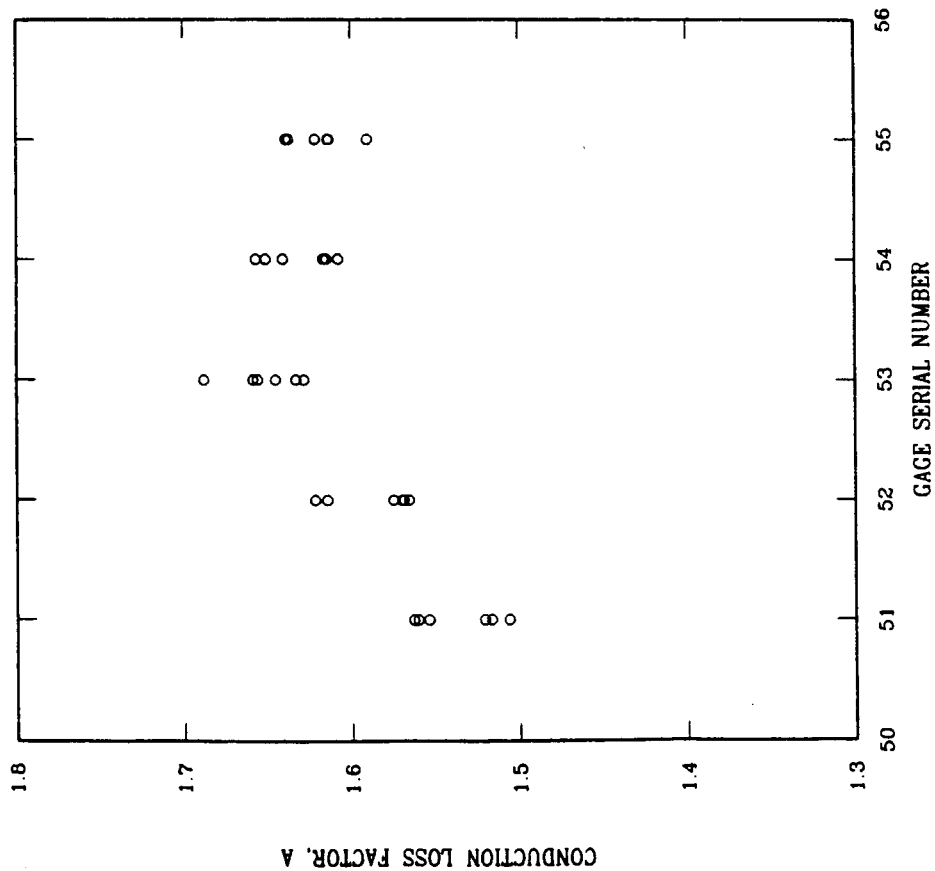


Figure 9

CONDUCTION LOSS FACTOR CALIBRATIONS FOR GAGES
BURIED WIRE GAGES #51 TO 55; Inst. Plug# 11; 10-29-85

GAGE NO.	TEMP COEFF OF RES., %/deg.C	RESISTANCE(ohm) AT 20 deg.C	COND LOSS FACTOR (AVE)
51	0.366	5.540	1.537
52	0.378	5.902	1.586
53	0.376	5.724	1.652
54	0.369	5.764	1.631
55	0.377	6.089	1.619



CONDUCTION LOSS FACTOR CALIBRATIONS FOR GAGES
BURIED WIRE GAGES #101 TO 107; Inst. Plug# 21; 7-7-86

GAGE NO.	TEMP COEFF OF RES., $\frac{\%}{\text{deg. C}}$	RESISTANCE(ohm) AT 20 deg. C	COND. LOSS FACTOR (AVE)
101	0.372	5.83	1.546
102	0.374	5.824	1.557
103	0.381	5.733	1.554
104	0.389	5.815	1.670
105	0.365	4.066	1.704
106	0.369	3.815	1.679
107	0.377	3.936	1.727

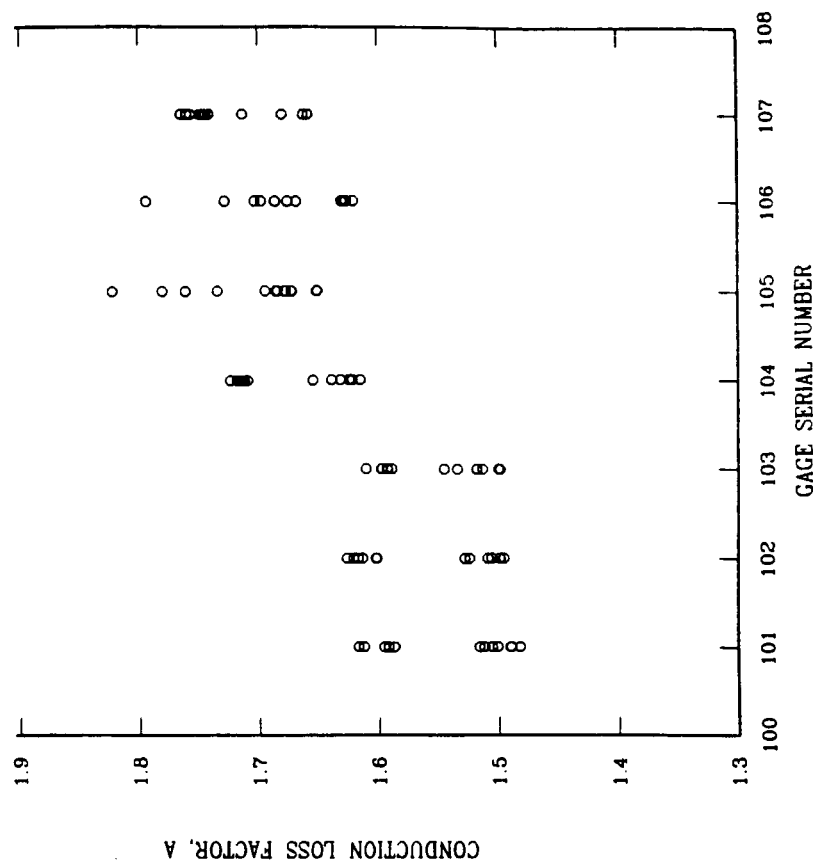


Figure 10